



环境保护部核与辐射安全中心

Nuclear and Radiation Safety Center

# IVR Design and Safety Demonstration of Advanced NPPs in China

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Vienna, Austria, 2017/6/7

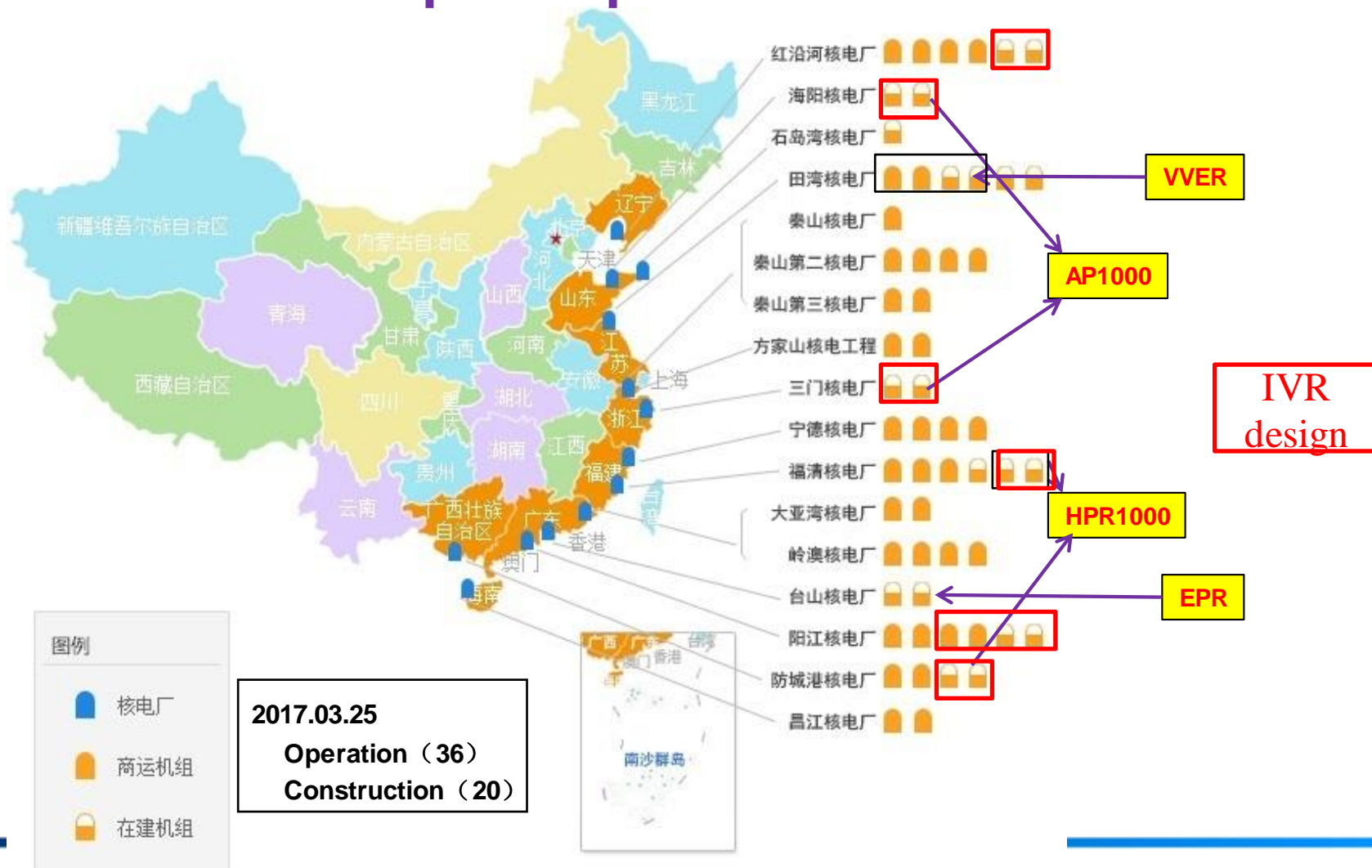


# Contents

- 1. Overview of SA design features in Chinese NPPs**
- 2. IVR Regulatory requirements in China**
- 3. IVR and Safety Demonstration of Advanced NPPs**
- 4. Conclusion**



### Overview of nuclear power plants in China mainland





# Main PWR types in China

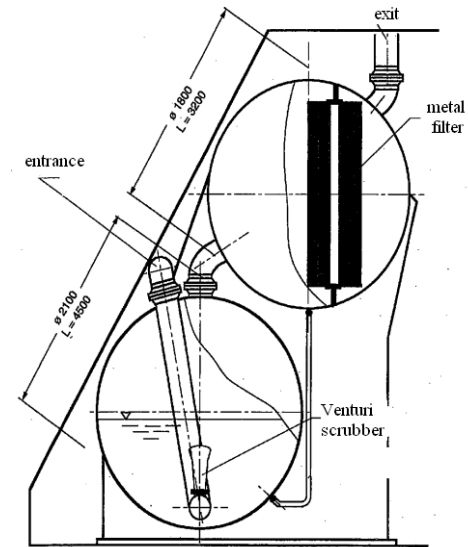
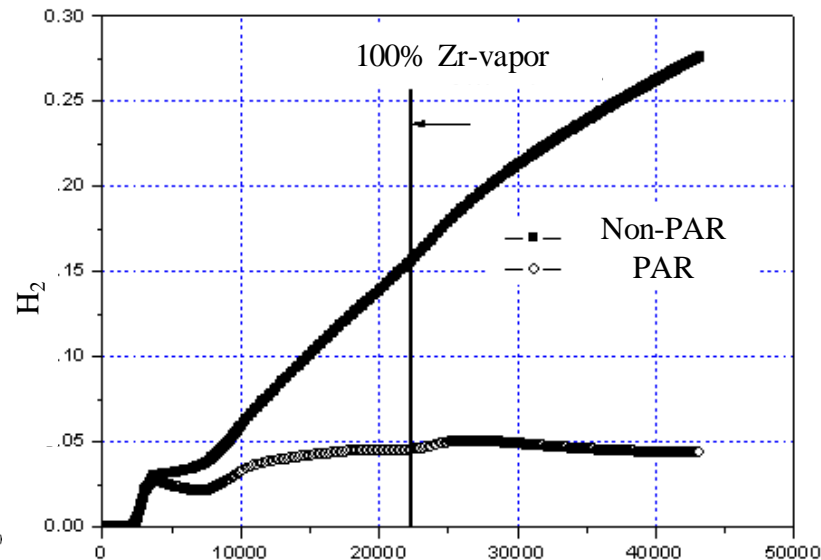
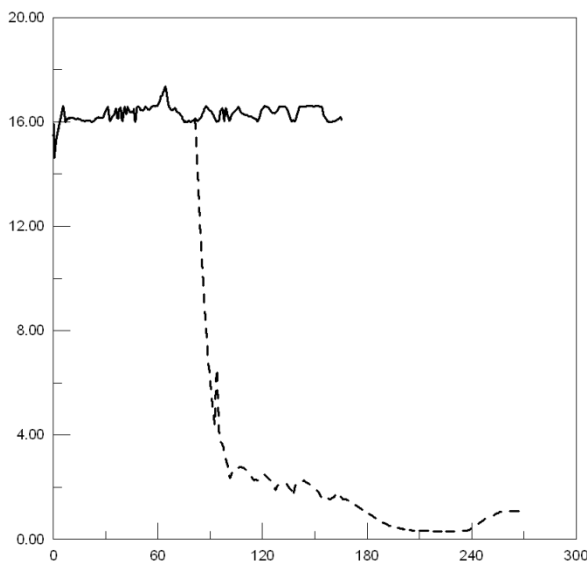
- Generation II+  $\rightarrow$  CPR1000<sup>+</sup>  $\rightarrow$  ACPR1000  $\rightarrow$  HPR1000
- AP1000  $\rightarrow$  CAP1400
- EPR
- VVER





### ■ Generation II+ $\rightarrow$ CPR1000<sup>+</sup> $\rightarrow$ ACPR1000 $\rightarrow$ HPR1000

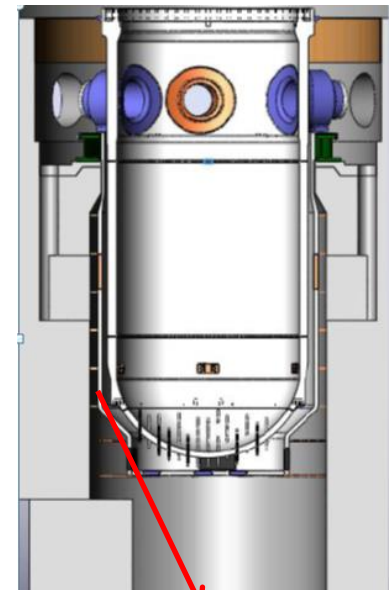
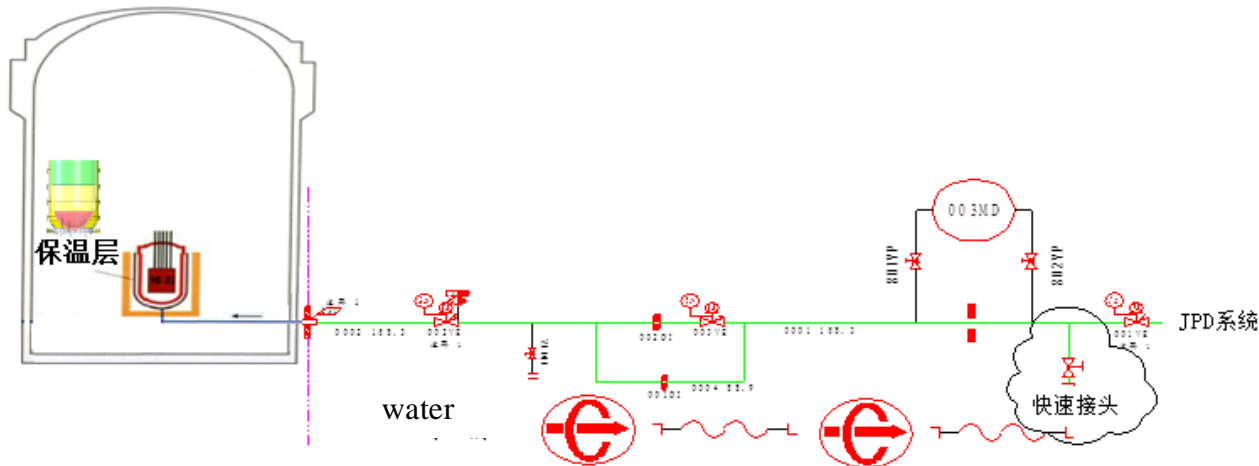
- Pressurizer depressurization function extension;
- The passive autocatalytic recombiners (PARs);
- Containment filtration and venting system.





### ■ Generation II+ $\rightarrow$ CPR1000<sup>+</sup> $\rightarrow$ ACPR1000 $\rightarrow$ HPR1000

- Pressurizer depressurization function extension;
- The passive autocatalytic recombiners (PARs);
- Containment filtration and venting system;
- IVR strategy
  - Water from fire protection system or portable supply

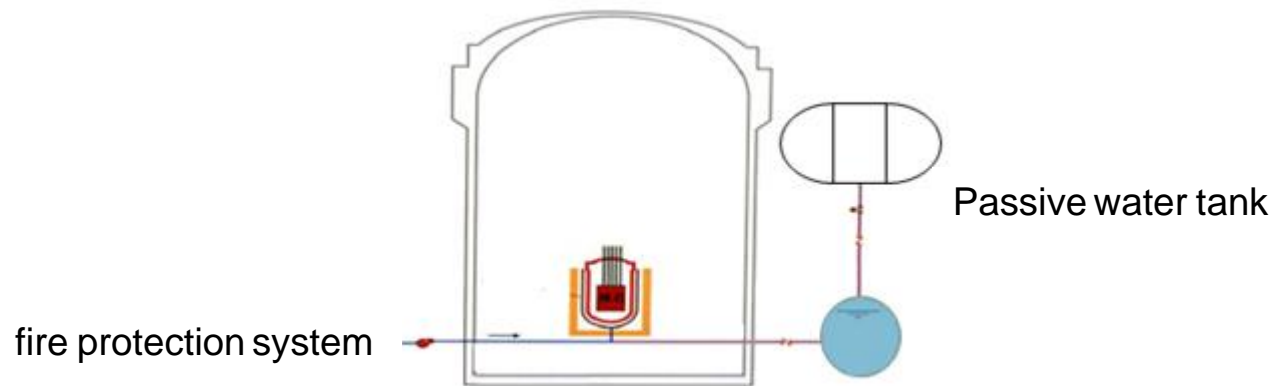


**Insulation  
modification**



### ■ Generation II+ → CPR1000<sup>+</sup> → **ACPR1000** → **HPR1000**

- Pressurizer depressurization function extension;
- The passive autocatalytic recombiners (PARs);
- Containment filtration and venting system ;
- **IVR strategy**
  - Water from fire protection system or portable supply
  - **Passive water tank for SBO condition**
  - **One serial dedicated depressurization system for severe accidents**





### ■ Generation II+ → CPR1000<sup>+</sup> → ACPR1000 → **HPR1000**

Comprehensive new severe accident prevention and mitigation features:

➤ **The dedicated depressurization system for severe accidents**

- ✓ Two redundant parallel discharge lines

➤ **The cavity injection and cooling system (IVR)**

- ✓ active subsystem
- ✓ passive subsystem

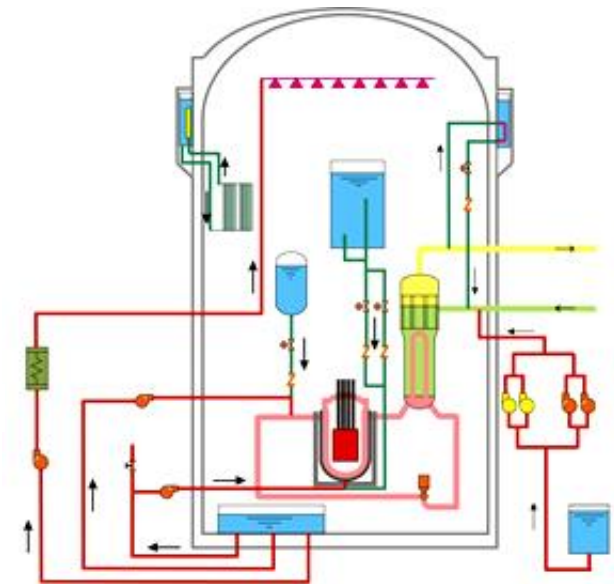
➤ **The passive residual heat removal system of secondary side**

➤ **The hydrogen control system**

- ✓ PAR or Hydrogen Igniter

➤ **The passive containment heat removal system**

➤ **The containment filtration and venting system**



**Active + Passive**





### ■ Generation II+ $\rightarrow$ CPR1000<sup>+</sup> $\rightarrow$ ACPR1000 $\rightarrow$ **HPR1000**

Comprehensive new severe accident prevention and mitigation features:



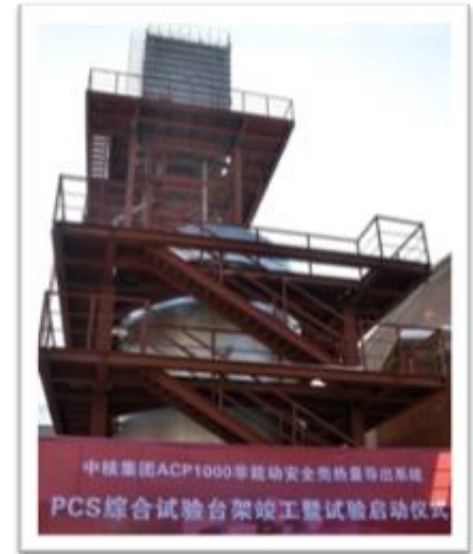
Reactor hydraulic  
integral test



Cavity injection  
and cooling system  
test



Passive residual heat  
removal system of  
secondary side test



Passive containment heat  
removal system  
performance test



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■ CAP1400/AP1000

■ EPR

■ VVER

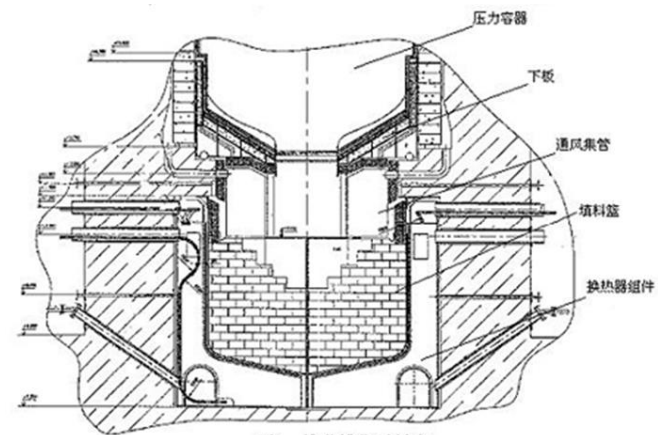
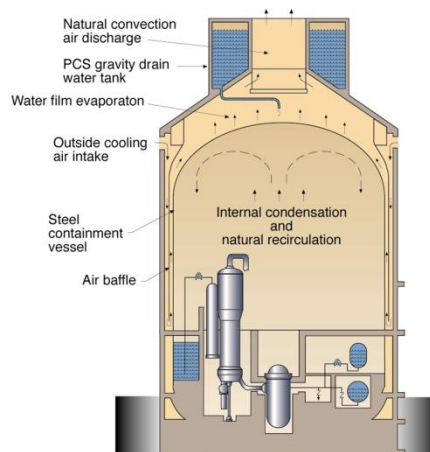
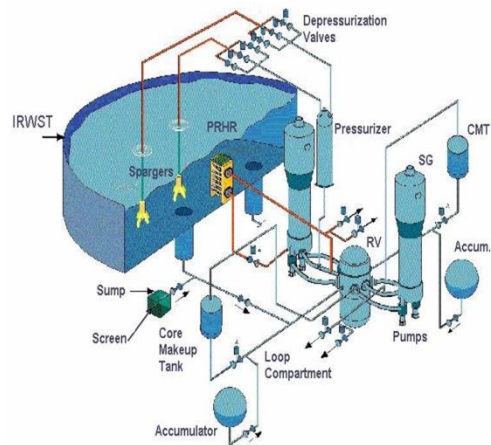
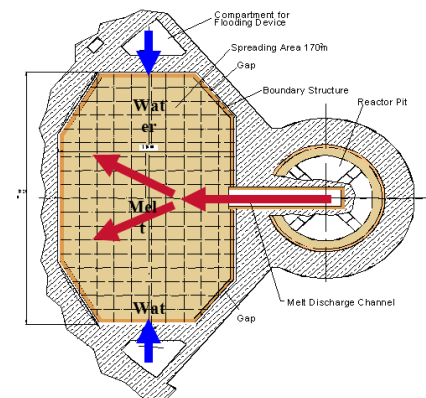
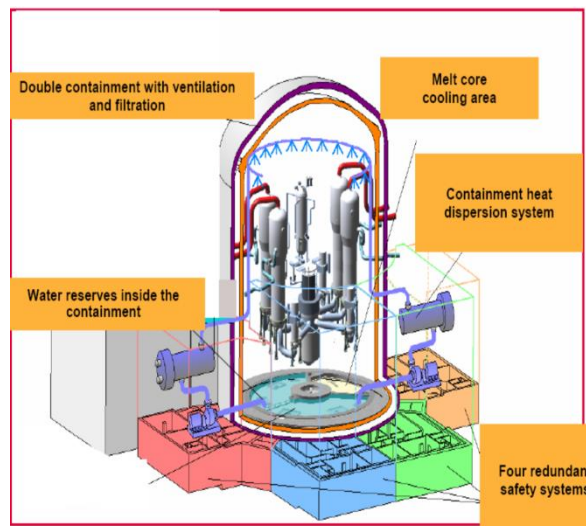


图1: 堆芯捕集器组成



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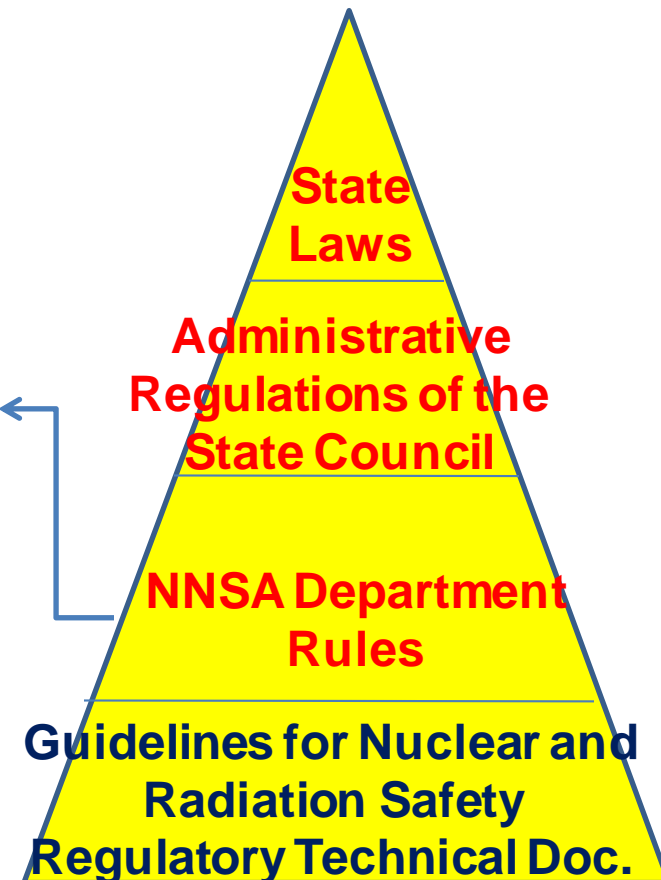
# IVR regulatory requirements in China

## ▪HAF 102 “Safety of Nuclear Power Plants: Design”

(Based on IAEA SSR-2/1, 2016)

*2.3.4 Plant event sequences that could result in high radiation doses or in a large radioactive release have to be ‘practically eliminated’.*

*6. 3. 5. 4 Design provision shall be made to prevent the loss of the structural integrity of the containment in all plant states.*







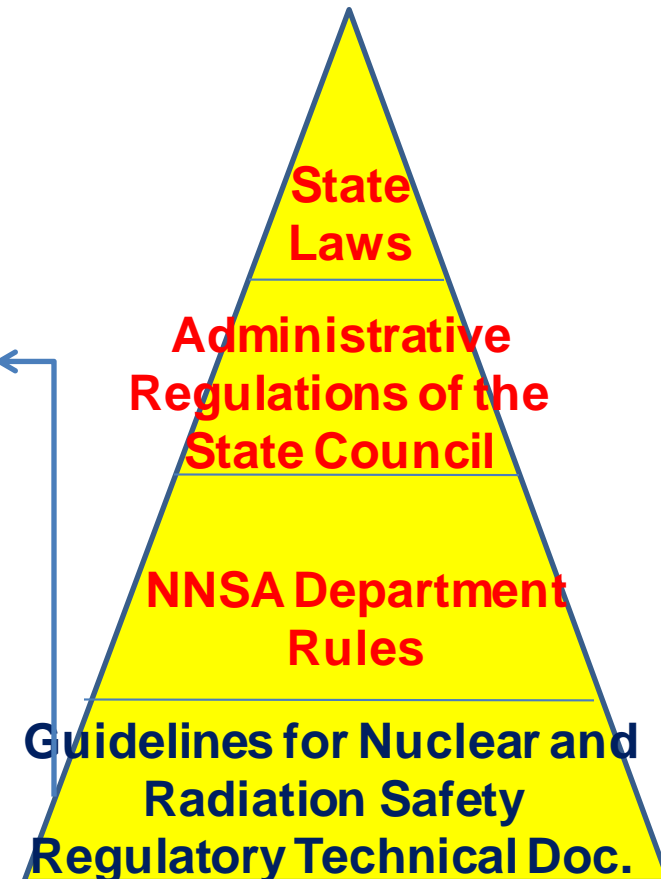
# IVR regulatory requirements in China

## ▪HAD 102/06 “Design of Reactor Containment Systems”

*(Based on IAEA No.NS-G-1.10)*

*6.2.5 Consideration should be given to incorporating into the plant design the following provisions to enhance the capability to cool molten core material and core debris, and to mitigate the effects of its interaction with concrete:*

- ✓ *A means of flooding the reactor cavity with water to assist in the cooling process or of providing enough water early in an accident to immerse the lower head of the reactor vessel and to prevent breach of the vessel;*
- ✓ *A reinforced sump or cavity to catch and retain molten core material and core debris (a core catcher).*





## New policy after Fukushima nuclear accident

### ■ Thirteen Five-year Plan and 2025 long-term goal for nuclear safety and radioactive pollution prevention and control

- “For new nuclear power units, the possibility of large scale radioactive release shall be made to practically eliminate in design”.

### ■ Safety requirements for new NPPs (draft)

- Adequate consideration shall be given to cool molten core debris, and to mitigate the effects of its interaction with concrete, a means of flooding the reactor cavity with water to prevent breach of the vessel, or a reinforced sump or cavity to catch and retain molten core debris should be adopted.



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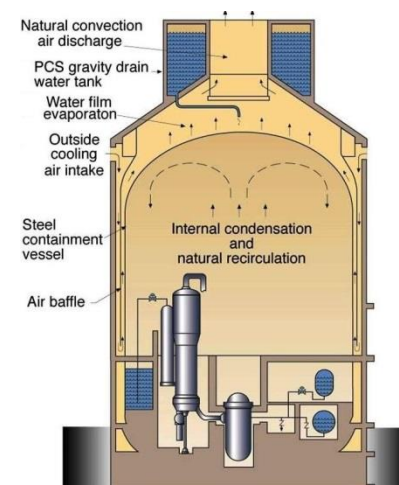
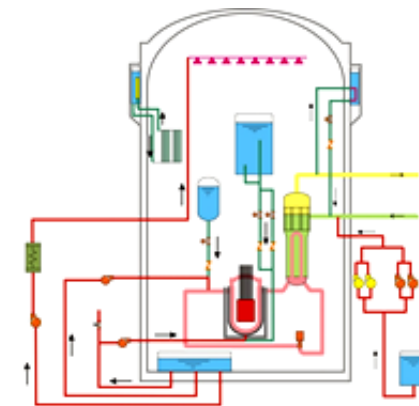
## IVR introduction of Advanced NPPs in China

### ■ IVR design

- HPR1000 (a): CNNC
- HPR1000 (b): CGN
- CAP1400: SPIC

### ■ IVR assessment

- Structural failure analysis
- Thermal failure analysis
- Cool effect due to water injection in RPV
- Steam explosion







## IVR design features of HPR1000(a/b):

- Dedicated depressurization system for severe accidents result in low stresses on the RPV wall.
- The vessel lower head has no penetrations, so there is no relevant failure mode.
- Flow path for the cooling water is formed as the annular gap between insulation and RPV, which enhances heat transfer between the RPV and cooling water.



## IVR system design of HPR1000(a)

### ■ Forced convection cooling

#### ➤ Active subsystem

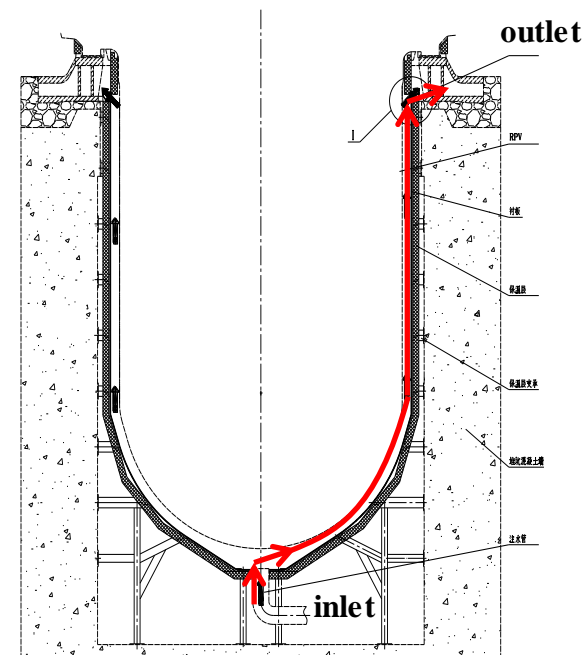
Non SBO condition.

- ✓ Two parallel connected injection lines, each equipped with an injection pump.
- ✓ Flow rate: 900t/h.
- ✓ IRWST as the water source, the water of Fire Water Distribution as backup.

#### ➤ Passive subsystem

SBO condition.

- ✓ Dedicated passive water tank in CTMT.





# IVR system design of HPR1000(b)

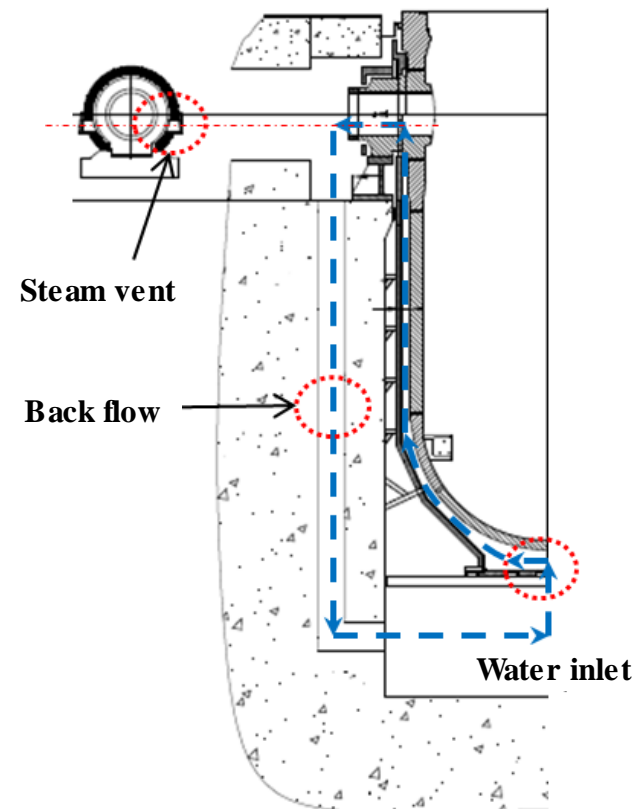
## ■ Natural convection circulation

### ➤ Passive injection phase

- ✓ Dedicated passive water tank in CTMT
- ✓ Reactor cavity will be flooded within 30min

### ➤ Active injection phase

- ✓ IVR pump will be used in long time phase, makeup the water vaporized
- ✓ IRWST as the water source
- ✓ Flow rate: ~40t/h.





# IVR system design of CAP1400

- Natural convection circulation similar with AP1000, but there are a lot of improvements, including enlarged capacity of ADS-4, more steel in reactor, etc.
  - Increase the capability of removing heat from the external surface of the reactor vessel (CHF).
  - Demonstrate thermal failure remains as the limiting failure over structural failure for the CAP1400.
  - Demonstrate that the CAP1400 in-vessel melt progression does not challenge the vessel integrity during relocation.
  - Demonstrate that the correlations used to calculate heat loads scale appropriately to the CAP1400.

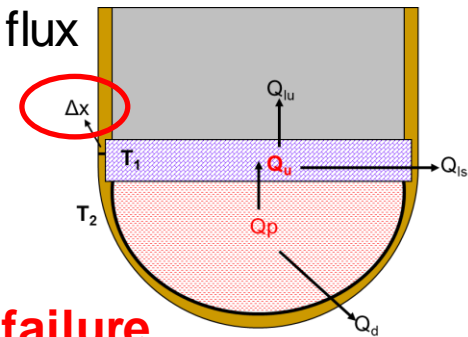




# Structural failure analysis

	$t_w$ (cm)	$t_{min}$ (cm)	times	$q_{peak}$ (MW/m <sup>2</sup> )
HPR1000(a)	0.8	0.02575	31	2
HPR1000(b)	0.82	0.00746	110	2
CAP1400	0.8	0.0198	40	2
<b>AP1000</b>	<b>0.8</b>	<b>0.022</b>	<b>36</b>	<b>2</b>

$t_w$ : RPV wall thickness conducting heat at the peak critical heat flux  
 $t_{min}$ : minimum thickness required to carry the dead load  
 $q_{peak}$ : conservative peak critical heat flux (actual  $q < 2.0 \text{ MW/m}^2$ )

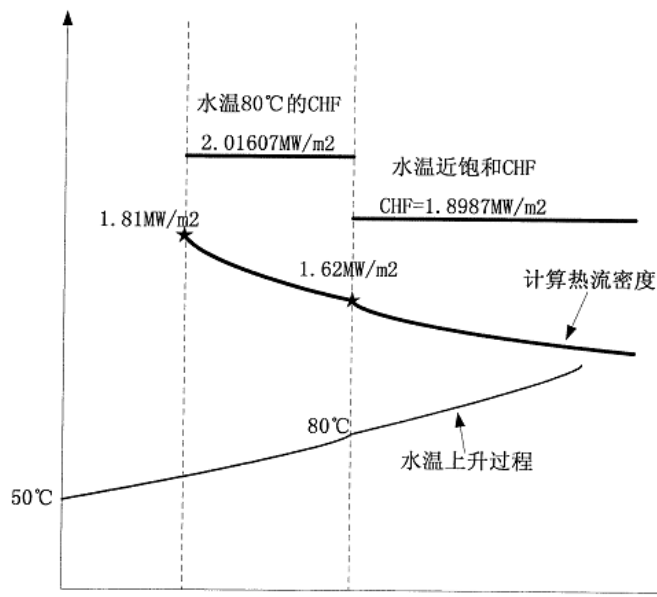


**Thermal failure is still the limiting failure mode over structural failure.**

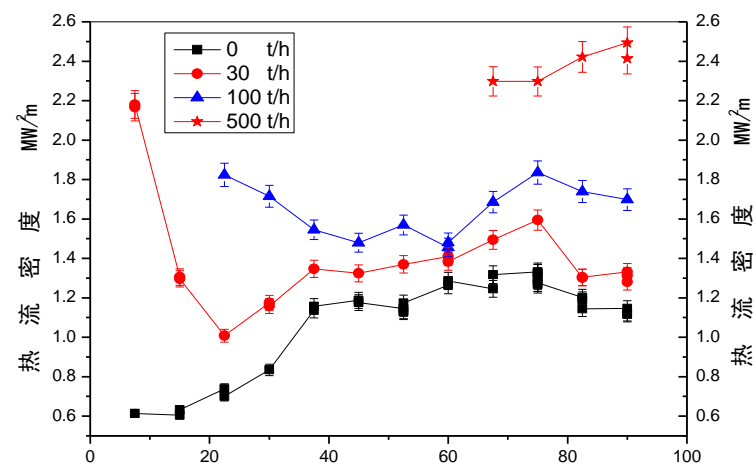


## Thermal failure analysis

- ROAAM analysis
- 2-layer model
- 1:1 slice CHF test



≈AP1000

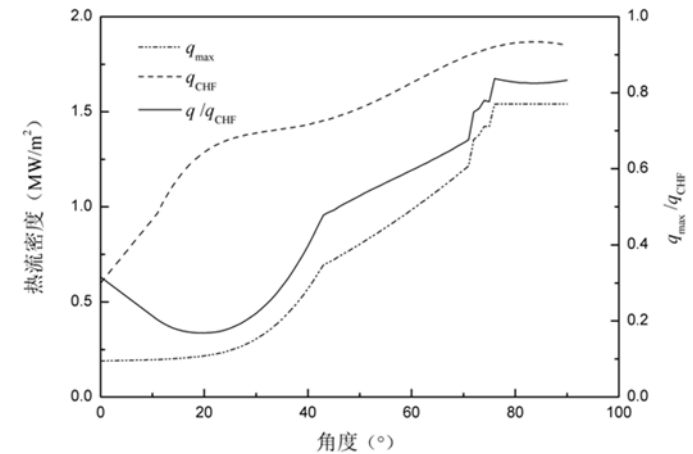
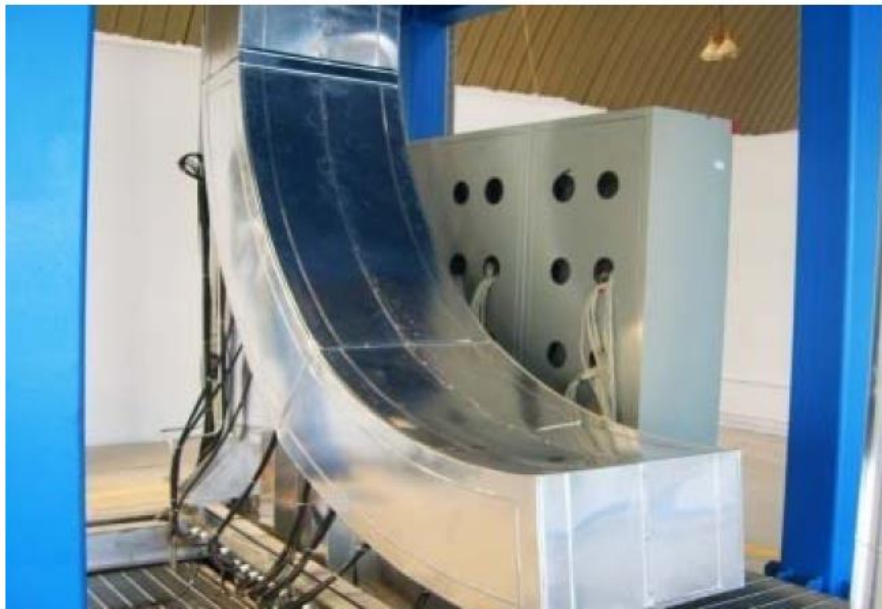


Dahuan Zhu, Introduction of NPIC Work on InVessel Retention(IVR) Strategy, Technical Meeting on Phenomenology and Technologies Relevant to In-Vessel Melt Retention and Ex-Vessel Corium Cooling. 17-21 Oct 2016. Shanghai, China.



# Thermal failure analysis

- ROAAM analysis
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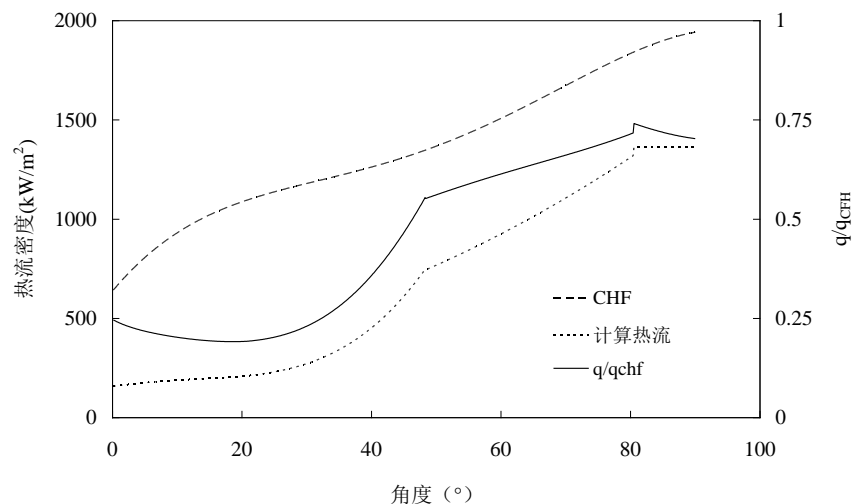
≈AP1000





## Thermal failure analysis

- ROAAM analysis
- 2-layer model
- 1:1 slice CHF test



≈AP1000







# Cool effect due to water injection in RPV

- After Fukushima Dai-ichi nuclear accident, injection to the RPV use portable facility is a necessary strategy for accident mitigation, it will
  - Prevent the core melt if adequate cooling geometry is maintained;
  - Reduce the melt portion if core melting is ongoing;
  - Enhance the heat transfer to the upper of the RPV if the molten pool formed.
- Water injection in RPV will benefit IVR.

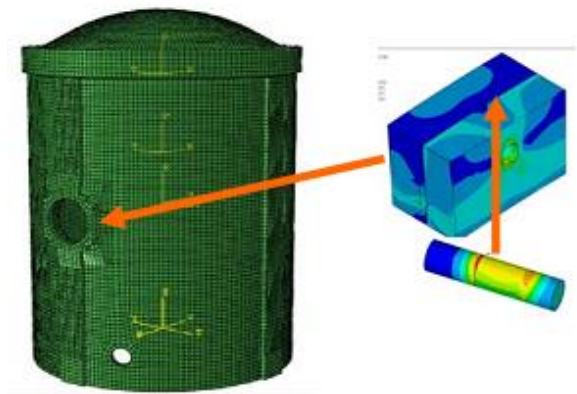
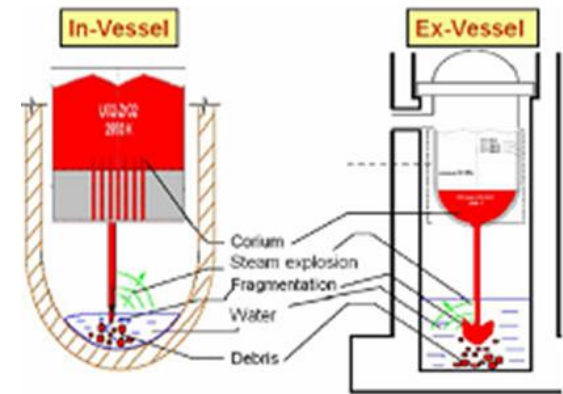


*Pei Jie, Chen Lian, Fan Haolong, Experimental studies of top-flooding to the high temperature corium in severe accident. The Seventh China-Korea Workshop on Nuclear Reactor Thermal-Hydraulics, WORTH-7. Kunming, 2015*



# Consequence of steam explosion outside the RPV

- If the IVR failed, there may be fuel-coolant interaction (FCI) and steam explosion, which will impact the integrity of the containment;
- In China, MC3D or TEXAS is used to simulate the steam explosion, the ABQUS or ANSYS is used to analyze the impact to the containment;
- The preliminary result shows local damage of the reactor cavity and the displacement of the penetrations will not affect the integrity of the containment.





## Conclusion

- Though there are still some uncertainties, NSC accepts the IVR design of advanced NPPs, and considers IVR as an effective severe accident strategy based on current experiment and analysis:
  - Structural failure assessment shows thermal success-criteria is still the limiting criteria;
  - The thermal load analysis shows considerable margin;
  - RPV water-injection strategy will benefit the IVR;
  - The deterministic analyses for ex-vessel FCI indicate IVR failure are not expected to result in containment failure.





## Conclusion

- Some studies are still needed to reduce the uncertainty or enhance the success probability of IVR analysis:
  - the core melt progression and molten core behavior in RPV lower head should be studied further, especially the experiment of prototypical reactor conditions,
  - the strategy to increase the efficiency of external cooling of RPV lower head, for example the use of the surface coating, should be studied further.
  - The uncertainty and mitigation of the steam explosion should be studied further.
- China will always spare no effort to support the severe accident relevant improvement and IVR research.





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**Thanks for  
your patience !**

